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Sustainable production of solar electricity with particular reference to the Indian economy

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Abstract

Fossil fuel reserves are diminishing rapidly across the world, intensifying the stress on existing reserves day-by-day due to increased demand. Not only that, fossil fuels, presently contributing to 80% of world primary energy, are inflicting enormous impacts on environment. Climatic changes driven by human activities, in particular the production of greenhouse gas emissions, directly impact the environment. Energy sector has a key role in this regard since energy during its production, distribution and consumption is responsible for producing environmentally harmful substances. A secure and accessible supply of energy is thus very crucial for the sustainability of modern societies. There is an urgent need for a quicker switch over of energy systems from conventional to renewables that are sustainable and can meet the present and projected world energy demand. Solar power is one of the most promising renewables. It is reliable and less vulnerable to changes in seasonal weather patterns. Hydrogen, in the capacity of energy vector, is expected to be the optimum solution for intermittency and storage of energy produced by renewables. Thus, coupled with hydrogen as an energy carrier, solar energy has a large potential to become the fuel of the future. The present study is aimed to explore such potential for India in 2025. India is expected to have a high growth rate in energy demand over the coming years due to its huge population and rapid economic development. By the year 2020, the country's demand for commercial energy is expected to increase by a factor of 2.5. Presently, more than 90% of the energy demand is met by fossil fuels, in spite of the fact that India has limited fossil fuel resources as compared to global reserves. By the year 2020, India, presently the world's sixth largest energy consumer, is expected to meet 75% of its oil and gas needs by imports. Being an energy deficient country, it has not been able to keep up with demand, leading to power shortages and supply interruptions. The growing gap between the demand and supply of energy, and environmental externalities associated with fossil fuel require immediate and substantial

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increases in electric power generation and transmission capacities, and exploitation of new avenues of energy supply that are more stable and environment friendly. The geographic location of India makes it a strong candidate for harnessing solar energy. Thus, solar PV is a potential technology to meet India's future energy demand and its associated environmental challenges. The present work proposes solar hydrogen based energy network to meet the future energy demand for the major cities of India in a sustainable way. In the proposed energy network, solar PV produced electricity is to be utilized to meet the energy demand during day hours. The solar generated electricity that is excessive of demand is to be stored in the form of hydrogen to be utilized during nocturnal hours and prolonged overcast conditions. A modular approach has been adopted for the purposed energy network to meet the year 2025 demand of six major cities of India: Chennai, Delhi, Jodhpur, Kolkata, Mumbai and Trivandrum. Present as well as projected cost scenarios for 2025 have been provided for all the proposed technologies to evaluate the economical viability of the energy network under study. Based on the futuristic trends, it is foreseen that by the year 2025, the PV electricity would be more economical than the fossil fuel electricity.

Keywords: Sustainability; Environmental impacts; Fossil fuel; Renewables; Photovoltaics; Hydrogen

Contents

1. Introduction

Energy is an essential element in human life. A secure, sufficient and accessible supply of energy is very crucial for the sustainability of modern societies. The demand for the provision of energy is increasing worldwide and will continue to rise as developing nations reach developed status and developed nations maintain their modernisation trends. Most predictions provide for the energy consumption growth of developed nations compounding at around 1% a year; however, for developing nations, consumption presently compound at over 5% a year.

Energy systems presently in use across the world can be classified into three main areas: fossil fuels, nuclear power and renewables. Fossil fuels in their crude form, i.e. wood and coal have traditionally been an extensive energy resource. More refined forms of fossil fuels, oil and gas, are still the dominant energy medium in the world. Nuclear power due to a number of reasons is not accessible to the vast majority of the world and has found its application only within developed countries. Renewable energy resources as compared, on the other hand, are easily accessible to mankind around the world. Renewables are not only available in a wide range, i.e. solar, wind, biomass and wave energies but are also abundant in nature.

The present energy situation, led by fossil fuels, has two major concerns namely, environmental impacts and depletion of resources. During energy use, varied stresses are created on the natural environment, some of which have global implications like the global warming, while others cause local impacts such as their effect on human health and ecology. Coal exploration and mining causes land degradation through subsidence and mine fires. The impact of mining on forest areas is of particular concern. Similarly, with onshore oil and gas production drilling waste fluids, drilling waste solids, produced water and volatile organics exhibit the potential to contaminate surrounding water bodies. Nuclear power has also serious reservations due to its associated radioactive emissions. Renewable energy sources, being clean and environment friendly, have a clear edge over the rest of energy systems.

Fossil fuel reserves are diminishing rapidly across the world. Stress on existing reserves is increasing day-by-day due to increased demand. It was reported in year 2003, that reserve to production ratio of fossil fuels for North America, Europe and Eurasia, and Asia Pacific was 10, 57 and 40 years, respectively, as shown in Fig. 1 [1]. Research conducted at

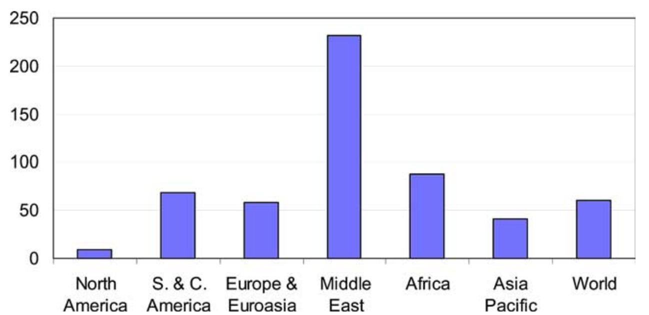


Fig. 1. Reserves to production (R/P) ratio—2002 estimates.

the University of Uppsala in Sweden claims that oil supplies will peak soon after 2010, and gas supplies not long afterwards, making the price of petrol and other fuels rocket with potentially disastrous economic consequences unless people have moved to alternatives to fossil fuels [2].

Nuclear power due to its associated environmental and political concerns is not a likely candidate to replace fossil fuels after the latter run out. In this respect, Germany, for example, took major steps in November 2003 towards ending its nuclear power programme when it shutdown the first of its 19 atomic power stations. The shutdown followed an agreement signed with the industry in the year 2000 to close all the nuclear power plants by 2025. Several other European countries are preparing to follow Germany's lead, with both Belgium and Sweden announcing nuclear phase-out plans [3].

Consequently, all the aforementioned reasons concur the need to consider renewables as the alternative energy systems. Amongst the renewables, solar and wind energies are receiving more attention than the others. Solar energy, however, has a significant advantage over wind energy, as the former is more abundant and more predictable. Wind speed, for example, can gust from 48 to 192 km h in 3 s, which is a tremendous change for engineers to design for [4]. Renewable energy can be stored in the form of hydrogen fuel to meet the energy demand during dry spells, i.e. hours when sun is not shining.

India's population is expected to reach 2289 million by the year 2051 [5]. Huge population and development activities are assumed to increase India's energy demand tremendously over the coming years. This work presents the energy scenario of India in terms of its total energy demand and supply and its context within the world community. The renewable energy prospects of India have been highlighted herein. Furthermore, prospects of solar hydrogen to be used, to meet the energy demand of six major energy consuming Indian conurbations: Chennai, Delhi, Jodhpur, Kolkata, Mumbai and Trivandrum, have been explored. Fig. 2 shows the geography of these locations.

2. The global environmental scene

The global environmental scene has changed dramatically over the last century. Climatic changes driven by human activities, in particular the production of greenhouse gas emissions (GHG), directly impact the environment. Energy sector has a key role in this regard since energy during its production, distribution and consumption is responsible for producing environmentally harmful substances.

Human activities release greenhouse gases into the atmosphere. CO_2, one of the most important greenhouse gases, is produced when fossil fuels are used to generate energy and when forests are cut down and burned. Methane and nitrous oxide are emitted from agricultural activities, changes in land use, and other sources. Halocarbons (CFCs, HFCs, PFCs) and other long-lived gases such as sulphur hexafluoride (SF_6) are released by industrial processes.

For the last 150 years, industry has been releasing CO_2 into the atmosphere at a rate of millions of times greater than the rate at which it was originally accumulated underground. Deforestation alone has been responsible for around 20 Gt of carbon since 1800. The mean global surface temperature has increased by 0.4–0.8 °C in the last century above the baseline

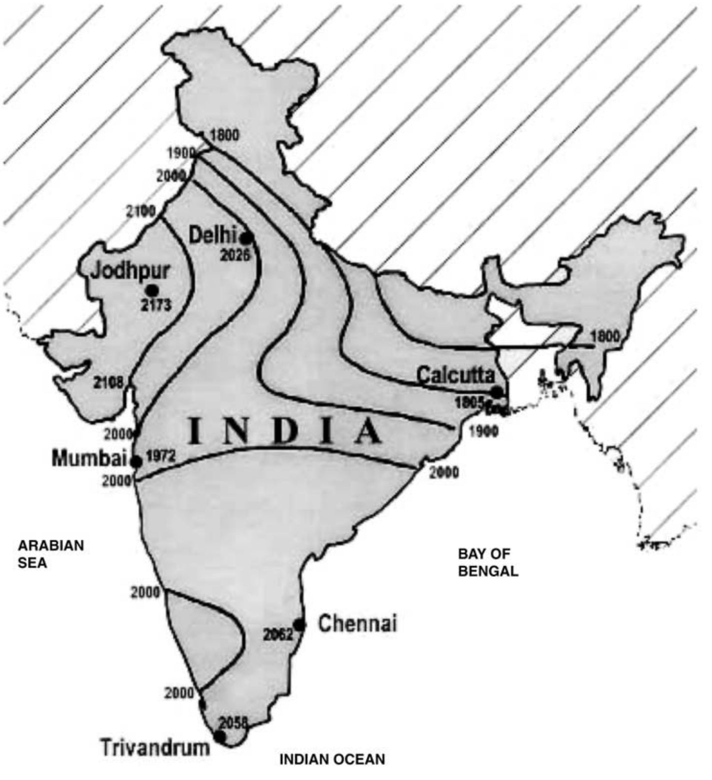


Fig. 2. Locations considered in the present work and the distribution of annual global solar irradiation, kW h/m^2.

of 14 °C [6]. If nothing is done, global temperatures could rise by up to 6 °C by 2100. The current rates of CO_2 emitted by industrialised nations are typically in excess of their sustainable limits. Table 1 shows the alarming status of CO_2 emissions [7]. Global warming and its associated climate changes are inflicting disastrous impacts on human health, economics and environment of the planet. According to the World Health Organisation, as many as 160,000 people die each year from the side effects of climate change and the numbers could almost double by 2020 [8]. Economic losses as a direct result of climate change are also immense. Between the 1960s and the 1990s, the number of significant natural catastrophes such as floods and storms rose many-fold, and the associated economic

Table 1
Status of carbon emissions

Country	Emissions of carbon equivalent in kilogram per person per year (base 2000)	Factor by which present emissions exceed sustainable level (of 500 kg/person per year)
US	6718	13.4
Germany	3292	6.6
France	2545	5.1
India	247	0.5

losses rose by a factor of 9. Figures indicate that the economical losses as a direct result of natural catastrophes over 5 years between 1954 and 1959 were US$ 35 billion, while between 1995 and 1999 these losses were around US$ 340 billion [9]. Around the world, ice sheets and glaciers are melting at a rate unprecedented since record keeping began. Changes in the area and volume of the two polar ice sheets in Antarctica and Greenland are intricately linked to changes in global climate and could result in sea-level changes that would severely affect the densely populated coastal regions on Earth. Research undertaken by Australian scientists has revealed new evidences of global warming, suggesting that sea ice around Antarctica had shrunk 20% in the past 50 years. The change is important because sea ice—the area around the poles where seawater is frozen into layers no more than a few metres thick—is regarded as a crucial indicator of climate change [10].

Compared with the 304 Gt of carbon emitted since 1860 from the burning of fossil fuels, four times that amount is contained in the known reserves of oil, gas and mainly coal that could be recovered in the near future, based on existing economic and operating conditions. Moreover, if the estimated and unconventional reserves (which includes oil shales, tar sands, coal bed methane, and deep geopressured gas) are fully exploited, the net amount of carbon emitted would soar to 16 times the value until 1998 as shown in Table 2 [6].

If GHG emissions are unabated, natural catastrophes inflicting damage to ecology of the planet and its inhabitants are expected to occur more frequently and intensely in future. Physical infrastructure will be damaged, particularly by sea-level rise and by extreme weather events. Water resources will be affected as precipitation and evaporation patterns change around the world.

The way to repair the already inflicted damages of global warming and a rather safe escape from the anticipated threats is an immediate change in the overall energy sector. There needs to be a global drive on two fundamental fronts: firstly to conserve energy and to increase the efficiency of existing energy resources, secondly to switch the energy systems from existing energy resources to renewables that are clean and environment friendly.

3. The global energy problem

3.1. Energy systems

Historically, fossil fuels have been the main source of energy supply and have served the human energy needs for thousands of years. With the advent of industrial revolution in

Table 2
Atmospheric carbon emissions (Gt C) from fossil fuel use since 1860 compared with remaining known and unconventional reserves and resources on a global scale

Status of reserves	Oil	Gas	Coal	Total
Known reserves	109	87	1111	1307
Estimated reserves	158	180	2606	2944
Unconventional reserves	446	297	–	743
Cumulative emissions	713	564	3717	4994[a]
Emissions from 1860 to 1998	109	43	152	304

[a] Potential emissions from exhaustive consumption of fossil fuels.

19th century, fossil fuels saw their refined liquid phase, oil that is more efficient than their traditional solid phase counterparts (wood and coal). More recently, world became familiarised with gaseous phase of fossil fuels that is ever more efficient. Renewable energy sources have also been important for humans since the beginning of civilisation. Biomass, for example, has been used for heating, cooking and steam production—and hydropower and wind energy, for transport and later for electricity production. In developed countries, by the middle of last century, fossil fuels and renewables were accompanied by a new energy system, nuclear power, to meet their energy needs.

At present, fossil fuels are still the most important sources of world's primary energy supply. Renewable energy sources (including biomass, solar, wind, geothermal, and hydropower) that use indigenous resources have the potential to provide energy services with zero or almost zero emissions of both air pollutants and greenhouse gases. They have now been acknowledged as a vital and plentiful source of energy that can indeed meet entire world's energy demand.

It is interesting to note that way back in 1923, Haldane prophesied the production of hydrogen in the UK by renewable energy means. He writes thus, "The country will be covered with rows of metallic windmills working electric motors which in their turn supply current at a very high voltage to great electric mains. At suitable distances, there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen. These gases will be liquefied, and stored in vast vacuum jacketed reservoirs, probably sunk in the ground. In times of calm, the gasses will be recombined in explosion motors working dynamos which produce electrical energy once more, or more probably in oxidation cells" [11].

3.2. Status and trends

Oil reserves around the world are diminishing and environmental concerns surrounding the use of fossil fuels are increasing. Fossil fuels still hold the major share of global energy supply. According to International Energy Agency statistics, fossil fuels supply 80% of world's primary energy [12].

Nuclear power plants, presently supplying 6.9% of the global energy demand, are clean and efficient to operate. However, they have serious environmental implications. Nuclear power plants produce radioactive gases. These gases are to be contained in the operation of the plant. If these gases are released into the air, major health risks can occur. Nuclear plants use uranium as a fuel to produce power. The mining and handling of uranium is very risky and radiation leaks can occur. The third concern of nuclear power is the permanent storage of spent radioactive fuel. This fuel is toxic and its handling and disposal is an ongoing environmental issue for centuries.

Renewable energy sector at present is meeting 13.5% of the global energy demand. This sector is now growing faster than the growth in overall energy market. Some long-term scenarios postulate a rapidly increasing share of renewable technologies (made up of solar, wind, geothermal, modern biomass, as well as the more traditional hydro). Under these scenarios, renewables could reach up to 50% of the total share of mid-21st century with appropriate policies and new technology developments. The trend for the period

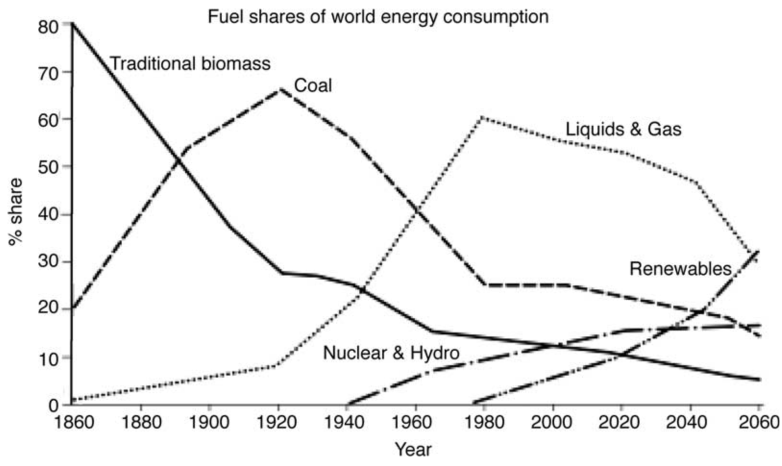


Fig. 3. Historical and future trends of energy systems.

2000–2060 provides one possible scenario of future energy consumption that shows renewables having the highest share as shown in Fig. 3 [13].

A large number of renewable-based activities are being undertaken on national and international platforms around the world. Diminishing reserves of fossil fuels and environmental concerns associated with both fossil fuels and nuclear power are beginning to drive the energy sector worldwide to strive towards renewable energy sources adopting hydrogen as the energy carrier.

The transition of world energy system to hydrogen—the simplest and most abundant element in the universe—as a fuel is quite logical and becomes clearer when one takes a look at historical energy production sequence. Each successive transition from one source to another—from wood to coal, from coal to oil—has entailed a shift to fuels that were not only harnessed and transported more economically, but also had a lower carbon content and higher hydrogen content. It is also evident that at each step greater energy density is being achieved. The third wave of decarbonisation is now at its threshold, with natural gas use growing fastest, in terms of use, among the fossil fuels. The fourth wave, the production and use of pure hydrogen, is certainly on the horizon. Its major drivers are technological advances, renewed concern about the security and price of oil and gasoline, and growing pressure to address local air pollution and climate change.

3.3. Future challenges and prospects

Access to electricity and other modern energy sources is a necessary requirement for the economic and social development of any country. It was projected by *The World Energy Investment Outlook* (WEIO) that if present trends continue, the world would need to invest US$ 16 trillion over the next three decades to maintain and expand energy supply. This number, much larger in real terms than the comparable figure for the past 30 years, is equivalent to 1% of annual global GDP over the period. The average annual rate of investment is projected to rise from US$ 455 billion in the decade 2001–2010 to US$ 632

billion in 2021–2030. This compares with estimated energy investment of US$ 413 billion in 2000. However, such high projected rates of investment will still leave 1.4 billion people without access to electricity in 2030, only 200 million fewer than now. World energy demand will rise by two-thirds by the year 2030, and the world economy will falter if adequate energy supplies are not made available.

The electricity sector will account for more than 70% of the above-mentioned figure of US$ 16 trillion, if the investments in the oil, gas and coal industries that are needed to supply fuel to power stations are included. World electricity demand will nearly double by 2030, and installed power generation capacity will increase from 3498 GW in 2000 to 7157 GW in 2030. In many countries investment in transmission and distribution will need to be even greater than that in power generation, in contrast to past patterns. Asia will account for 36% of global electricity investment, of which a considerable amount will be attributed to India [14].

Fossil fuels stocks are rapidly declining around the world. Today, the world burns as much oil in six weeks as it burned in 1 year in 1950 [7]. Expert estimations have put the timing of the 'big oil rollover' (when oil production will start to decline around the world) between 2005 and 2020 [15]. According to BP 2003 report, the reserve to production ratio of fossil fuels for world is 62 years as shown in Fig. 1 [1]. This is an alarming situation and there is an immediate need to explore other energy resources that are viable as well as environment friendly to avoid any further damage to global ecology.

Renewable energy sources have enormous potential and can meet many times the present world energy demand. They can enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and global atmospheric emissions. They can also provide commercially attractive options to meet specific needs for energy services (particularly in developing countries and rural areas), create new employment opportunities, and offer possibilities for local manufacturing of equipment. Major types of renewable energy sources include solar, wind, hydro and biomass, all of which have huge potential to meet future energy challenges.

Solar power is one of the most promising renewables. It is more predictable than wind energy and less vulnerable to changes in seasonal weather patterns than hydropower. Whereas generation of power from hydel, wind and geothermal sources is limited to sites where these resources exist in sufficient quantities and can be harnessed, solar energy can produce power at the point of demand in both rural and urban areas. Solar PV electricity is an equally significant energy option for developed and developing countries. Because of the cost of transmission lines and the difficulty of transporting fuel to remote areas, developing countries are increasingly turning to solar energy as a cost-effective way to supply electricity. With a third of the world's population still without electricity, most of whom live in developing countries, usage of solar PV modules will increase significantly as the demand for electricity spreads throughout the world.

Solar energy has the potential, not only, to play a very important role in providing most of the heating, cooling and electricity needs of the world, but also to solve our environmental problems. Much of it is underestimated, mainly because we do not see widespread commercial solar applications. However, some of the new emerging developments in solar technology are likely to change the situation. One of such

examples is, nanoscale antennas for direct conversion of sunlight to electricity with potential conversion efficiencies approaching 80–90% [16].

3.4. Solar hydrogen economy

3.4.1. Solar PV energy

Solar energy can be exploited through the solar thermal and solar photovoltaic (SPV) routes for various applications. While solar thermal technologies utilise the heat energy from the sun for various purposes, SPV technology enables direct conversion of sunlight into electricity through semi-conductor devices called solar cells. Solar cells are interconnected and hermetically sealed to constitute a photovoltaic module. The photovoltaic modules are integrated with other components such as storage batteries to constitute SPV systems and power plants. Photovoltaic systems and power plants are highly reliable and modular in nature.

Photovoltaic cells have been in use in spacecraft since the 1950s. However, with the energy crisis of the early 1970s, a steadily growing terrestrial industry has developed. Initially, it supplied PV cells mainly for remote area applications where conventional electricity is expensive. Nonetheless, the industry is now in an explosive period of growth where the subsidised urban-residential use of photovoltaics is providing the main market. The global industry had grown at a compounded rate of 30% per annum from 1996 to 2001, corresponding to a quadrupling of annual production over this period [17]. India, though on a smaller scale, is following similar trends. Fig. 4, for example, shows the world as well as Indian annual growth in PV modules shipments.

In places where there is enough solar potential, replacing coal with the former to generate power, can provide both commercial cost savings as well as carbon dioxide emission reductions. A comparison of the economics and emissions of some of the conventional electricity generation technologies against solar electricity generation has been provided in Table 3 [6].

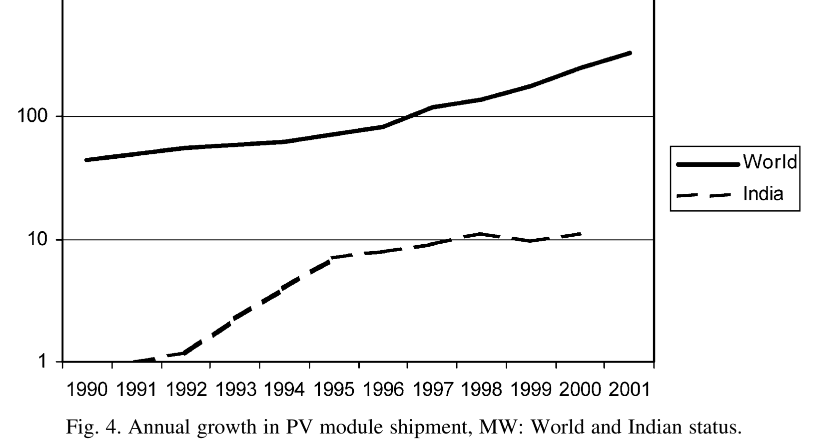


Fig. 4. Annual growth in PV module shipment, MW: World and Indian status.

Table 3
Economics and emissions of conventional technologies compared with solar electricity generation

Power generation technology	Carbon emissions (g C/kW h)	Emission savings (g C/kW h)	Generating costs (US¢/kW h)
Pulverized coal—as base case	229	0	4.9
Integrated gasification combined cycle (IGCC)—coal	190–198	31–40	3.6–6.0
Pulverised coal + CO_2 capture	40–50	179–189	7.4–10.6
Combined cycle gas turbine (CCGT)—natural gas	103–122	107–126	4.9–6.9
CCGT gas + CO_2 capture	14–18	211–215	6.4–8.4
Solar thermal and solar PV	0	229	8.7–40.0

The present market in the application of PV cells is defined by three sectors: the Professional sector, the Off-grid sector and the Grid-connected sector.

3.4.1.1. Professional sector. This sector represents, on one hand, the earliest exploitation route, viz remote telecommunications repeater stations, but also, on the other hand, futuristic technology, such as the US proposal for a 10 GW orbiting solar power station.

3.4.1.2. Off-grid or stand-alone sector. Stand-alone systems produce power independently of the utility grid. In some off-the-grid locations, as near as one-quarter mile from the power lines, stand-alone PV systems can be more cost-effective than extending power lines. They are especially appropriate for remote, environmentally sensitive areas, such as national parks, cabins and remote homes. In rural areas, small stand-alone solar arrays often power farm lighting, fence chargers and solar water pumps, which provide water for livestock. Direct-coupled systems need no electrical storage because they operate only during daylight hours, but most systems rely on battery storage so that energy produced during the day can be used at night. Some systems, called hybrid systems, combine solar power with additional power sources, such as wind or diesel.

3.4.1.3. Grid-connected sector. Grid-connected PV systems, also called grid interface systems, supply surplus power back through the grid to the utility, and take from the utility grid when the home system's power supply is low. These systems remove the need for battery storage, although arranging for the grid interconnection can be difficult. In some cases, utilities allow net metering, which allows the owner to sell excess power back to the utility.

In the last two decades, the cost of PV electricity has gone down by a factor of 10, and is expected to reduce further thus creating more potential [18]. Global demand of PV equipment has grown consistently by 20–25% per annum over the past 20 years. It is reported that in 2001 and 2002 global PV shipments were 395 and 525 MW, respectively. During 2002, world production of PV increased by a record 43.8% [19].

3.4.2. Hydrogen as the energy carrier

In present energy chain, collected or extracted primary energy is, in one or several steps, converted into energy carriers, such as diesel oil or gas that are suitable for end uses.

In future, it is expected that hydrogen will take over the role of energy carrier. Hydrogen in the capacity of energy vector will be the optimum solution for intermittency and storage of energy produced by renewables.

Hydrogen can be primarily produced through reformation of natural gas, electrolysis of water, or partial oxidation of heavy fossil fuels such as diesel. In a renewable energy scenario, solar PV energy will be utilised to carryout electrolysis of water to yield hydrogen.

As renewable-based energy systems evolve over time, hydrogen will provide an ideal storage medium. Hydrogen's potential use in fuel and energy application includes powering vehicles, running turbines or fuel cells to produce electricity and generating heat and electricity for buildings. Eventually, the hydrogen produced could replace fossil fuels in broader applications.

In order to move towards a sustainable hydrogen economy (an economy which relies on an energy system supported predominantly by the use of hydrogen), a future strategy must be outlined, followed, and continually revised. Around the world there are significant efforts being undertaken to strive towards hydrogen economy. Iceland, for example, has set targets to be the first country in the world to have the hydrogen economy that is through switching all its energy sources onto renewable-based hydrogen by around 2030–2040 [20]. In his 2003 State of the Union address, President Bush announced a US$ 1.2 billion initiative to reverse America's growing dependence on foreign oil by developing the technology for commercially viable hydrogen-powered fuel cells to power cars, trucks, homes and businesses with no pollution or greenhouse gases [21]. All major energy companies around the world are starting to position themselves towards the emerging hydrogen economy. BMW is developing hydrogen fuelled internal combustion engine passenger vehicles. Together with a fuel retailer, BMW intends to offer liquid hydrogen at refuelling stations in the vicinity of all BMW dealerships around Europe by 2005. Similarly, General Motors have committed themselves towards being the first automobile company to have 1 million fuel cell vehicles on the road. Shell and BP both have major hydrogen divisions within their companies.

4. The Indian energy scenario

4.1. Background information

The subcontinent of India lies in south Asia. It is a peninsula and the three sides are surrounded by Arabian Sea in the southwest, Bay of Bengal in the southeast and Indian Ocean in the South as shown in Fig. 2. India lies between 8.4 and 37.6° north latitude and 68.7 and 97.3° east longitude. It has a total area of 3,287,590 km^2, which is slightly more than one-third the size of US. India measures 3214 km from north to south and 2933 km from east to west. It has a land frontier of 15,200 km and a coastline of 7517 km. India shares its political borders with Pakistan and Afghanistan on the west, Bangladesh and Burma in the east, Nepal, China, Tibet and Bhutan in the north. The nation is divided into four large natural regions. The great mountain zone: the Himalayas, along the northern border; the fertile, densely populated Ganges plains immediately to the south, the desert region in the northwest and the Deccan plateau in the centre and south. Most of the country

lies in the tropics, and so stays warm throughout the year. The Himalayas shelter the country from cold north winds. The climate is subject to monsoon influence; hot and dry for eight months of the year, and raining heavily from June to September [22,23].

India has a population of 1,041,144,000 (2002 figures) with an annual growth rate of 1.8% (1985–2000) [24]. About half a billion people belong to middle class. Despite increased energy use in India, per capita consumption (3629 kW h) remains low as against the world average of 17,620 kW h. Indian per capita electricity use averages only one-sixth that of the world, one-half that of the Chinese, and less than one-twentieth that of North Americans [25]. Annual capacity additions have not been able to keep up with demand, leading to power shortages and supply interruptions. India is home to one-third of the world's poor [26]. There are 580 million people lacking electricity in India. Although the electricity network is technically within reach of 90% of the population, only 43% are actually connected because many poor people cannot afford the cost of connection. Even where incomes are high enough, households are often discouraged from connecting to the grid because of the poor quality of service, including frequent blackouts and brownouts. Over the last 5 years, Rural Electrification Corporation Limited (REC) has extended significant financial support to facilitate and accelerate the pace of electrification of villages and hamlets. Loan sanctions by REC witnessed growth of 79% amounting to US$ 2662 million in 2003 against US$ 1485 million sanctioned in the previous year [27].

In the year 2000, per capita GDP was reported to be US$ 2358 with an annual growth of 2.0% and an annual inflation of 4.0% [24]. India's GDP is composed of agriculture—25%, industry—30% and services—45%. Main industries include, textiles, chemicals, food processing, steel, transportation equipment, cement, mining, petroleum and machinery.

4.2. Energy demand and supply

India accounted for 3.5% of world primary consumption and 12% that of total primary energy consumed in Asia-Pacific region in 2002 [1]. The country is the world's sixth largest energy consumer and indeed a net energy importer. India is a vast country with diverse mix of resources. The energy consumption is attributed to a number of fuels with varying use patterns. Table 4 describes various fuels that share India's energy market.

Coal dominates the energy mix in India, meeting about 60% of energy requirements in the country. Nearly, 30% of India's energy needs are met by oil, and more than 60% of that oil is imported. Natural gas has experienced the fastest rate of increase of any fuel in India's primary energy supply. Presently, the natural gas contribution is met entirely by

Table 4
India's energy consumption by fuel (year 2002)

Fuel	Consumption (M to E)	Share of total
Coal	180.8	55.6
Oil	97.7	30.0
Natural gas	25.4	7.8
Nuclear	4.4	1.4
Hydro	16.9	5.2
Total	325.1	100.0

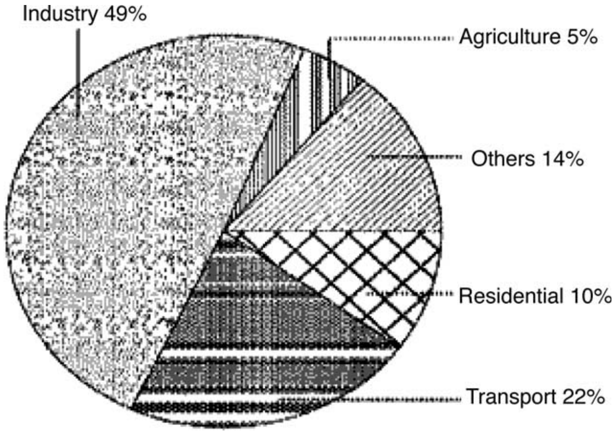


Fig. 5. Indian sectoral composition of commercial energy consumption: 1999/2000.

domestic production. However, the gap between demand and supply is set to widen unless major gas discoveries are made. It is expected that by 2010 almost three-quarters of India's oil and gas needs will be met by imports [28].

Industrial sector is the largest consumer of energy in India, consuming about half of the total energy consumption in 1999/2000. The transport sector is the next biggest consumer at 22% of total commercial energy consumption. Fig. 5 shows the sectoral composition of commercial energy consumption in India. It consumes nearly half of the oil products, mainly in the form of diesel oil and gasoline. Agriculture sector mainly consumes electric power and diesel oil, major portions of which go into pump sets used for irrigation purposes. Residential sector is another significant consumer in India. Traditional biomass accounts for more than a third of the energy consumed in the Indian household sector. A detailed account on the use of biomass in India has been presented by Ramachandra [29]. It is estimated that out of the total household sector energy needs, 30% is consumed in lighting, 1% in cooking and the rest by other household appliances [25]. Indian electric power sector now consumes over 40% of primary energy, with an overwhelming contribution by coal (70%), hydroelectricity (25%), followed by natural gas, nuclear power, oil and renewables, which account for the remaining 5% [30].

The all-India installed generating capacity increased from a meagre 1362 MW in 1947 to 101,630 MW in early 2001, a gain of nearly 75 times in capacity addition. The demand of electricity in India is enormous and is growing steadily. Electricity use has more than doubled in the last decade, and has grown faster than GDP for the past 20 years [31]. Electricity consumption per person has increased to over 493 kW h in 2001, up from 90 kW h in 1972 [12]. The energy demand, GDP and population are predicted to increase significantly within the next two decades as shown in Fig. 6.

4.3. Energy and environmental challenges

For India to tackle the economic and environmental challenge of its energy demand growth, it is important to have a good understanding of how these and other factors shape

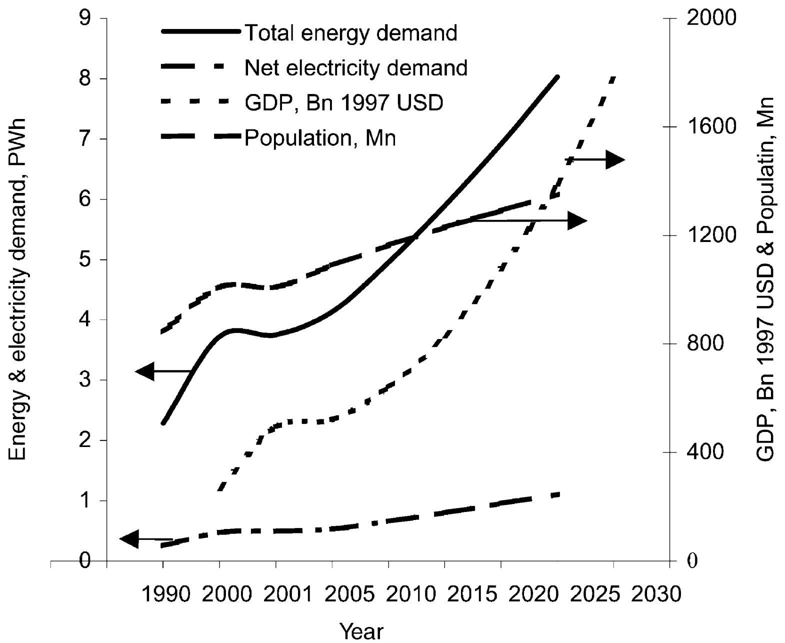


Fig. 6. Energy, economic and population trends for India.

energy use in various sectors of the economy. Detailed and coherent information is needed in order to judge the potential for energy efficiency improvements or to measure the progress of already implemented policies.

India's rapidly growing economy will drive energy demand growth at a projected annual rate of 4.6% to the year 2010 [30]. It has been reported that India's electric power demand are likely to increase threefold by the year 2051. Indications are that the electric power demand is expected to grow at around 10% per annum in next 15 years requiring about 10,000 MW of capacity addition every year over this period [5]. Other studies indicate that by 2020, India's demand for commercial energy is expected to increase by a factor of 2.5 [32]. Underpinning this trend will be the ongoing growth in population, urbanization, industrial production and transport demand.

Energy shortages in India have been increasing in the past few years, from 5.9% in 1998/1999 to 7.8% in 2000/2001. The peak energy demand during 2001–2002 touched 86 TW h, of which only 75 TW h could be met. India will continue to experience this energy supply shortfall for at least another 15 years. This gap has been exacerbated since 1985, when the country became a net importer of coal [30]. The growing gap between the demand and supply of energy, and environmental externalities associated with energy use are the key issues today. Almost half of India's trade deficit is due to petroleum imports, the cost of which also limits capital that could be invested in the economy [30]. High economic development requires rapid growth in energy sector. This implies substantial increases in electric power generation and transmission capacities, and exploitation of new avenues of energy supply.

Table 5
Indigenous fossil fuel reserves in India

Resource	Proved reserves	Expected life of reserves (years)
Coal (MT)	84,396	235.0
Natural gas (BCM)	760	26.9
Oil (MT)	700	19.4

Nuclear energy contributes 2% to India's total power generation. Indications are that the share would be even less in 2010 due to many unsolved problems like high cost, radioactive wastes and decommissioning costs [33]. In 2002, India's oil consumption raised to 97.7 million tonnes, more than 2.6 times the domestic production [1]. Estimates indicate that oil imports will meet 75% of total oil consumption requirements and coal imports will meet 22% of total coal consumption requirements in 2006 [33]. India can ill afford to overly depend on fossil fuels considering the high cost of imported petroleum products. India's fossil fuel resources are limited compared to global reserves. Table 5 provides an estimate of fossil fuel reserves in India.

The Indian economy has grown two and a half times over the past two decades but pollution control has not kept pace; industrial pollution has quadrupled over the same period. The Indian government has estimated the cost of environmental degradation at about 4.5% of GDP in recent years [28]. Indiscriminate and inefficient burning of fuel wood in traditional cookers and in industries for thermal process heat has resulted in deforestation, environmental pollution and health hazards. Another significant problem is the generation of fly ash during the combustion of coal in power generation. In India with 70% of power generation being coal-based and the inherently high ash content of indigenous coal (more than 40% in some cases), 80–100 million tonnes of fly ash are produced every year. India stands second only to China in the quantum of fly ash generated every year. Currently, nearly 90% of fly ash generated is dumped as slurry in ash ponds, which requires huge amounts of water, resulting in creation of wasteland which also leads to leaching of heavy metals and soluble salts. Leakage from ash ponds to neighbouring fields and water bodies can lead to surface and groundwater pollution. The utilization of fly ash in India remains low at 10%, compared with utilization rates of 30–100% internationally [33]. The use of gasoline and diesel in the transport sector generates a number of pollutants like lead, carbon monoxide, toxic compounds such as benzene, and particulate matter which are discharged to the atmosphere along with vehicular exhaust gas. India is currently the fifth largest carbon emitter in the world, behind only the US, Russia, China and Japan; India's fossil fuel carbon emissions are about the same as for the entirety of Africa. In the past decade alone, India's carbon emissions have increased by about 60%, and are about nine times higher than they were 40 years ago [28]. Much of this increase is due to India's increasing utilization of its coal resources for power generation. Carbon emissions are forecast to grow by about 3% annually through 2025, as against 1.9% of the total world as shown in Table 6. To limit the disastrous effects of global warming, Indian as well as the world's CO_2 emissions would have to be cut by 50% [7].

Table 6
CO_2 emissions by fuel use (million metric tons carbon equivalent), reference case, 1990–2025

Resource	India								Average annual percentage change, 2001–2025	
	History			Projections						
	1999	2000	2001	2005	2010	2015	2020	2025	India	World
Coal	101	161	162	172	194	212	229	261	2.0	1.6
Oil	45	76	76	81	100	126	160	195	4.0	1.8
NG	7	12	12	19	27	37	46	50	6.1	2.8
Total	153	249	250	272	321	375	435	506	3.0	1.9

4.4. Renewables trends

During the past decade, India has taken steps to utilise the immense potential for renewable energy sources. The goals of Indian energy planning include the promotion of decentralised energy technologies based on renewable resources in the medium term, and the promotion of energy supply systems based on renewable sources of energy in the long term. The latest projection by the Ministry of Non-conventional Energy Sources plan additional 12 GW capacity by 2012.

There is a large potential of renewable energy resource available in India, an estimated aggregate of over 100,000 MW, which needs to be harnessed in a planned and strategic manner to mitigate the gap between demand and supply. In the present scenario, renewable energy is contributing to about 3.5% of the total installed electric capacity of about 3700 MW. It is planned to increase this to 10% of the total power generation capacity by the year 2012.

Today India has the largest decentralised solar energy programme, the second largest biogas and improved stove programmes, and the fifth largest wind power programme in the world. Table 7 describes India's renewable energy potential and achievements [18].

However, only a fraction of the aggregate potential in renewables, and particularly solar energy, has been utilized so far. The achieved wind power capacity is less than 4% of

Table 7
Renewable energy potential and achievements in India

Energy sources	Potential	Achievement as on 31.12.2002	India's position in the world
Biogas plants	12 million	3.37 million	Second
Improved Chulhas	120 million	33.9 million	Second
Wind	45,000 MW	1702 MW	Fifth
Small hydro	15,000 MW	1463 MW	Tenth
Biomass power/cogeneration	19,000 MW	468 MW	Fourth
Biomass gasifiers		53 MW	First
Solar PV	20 MW/km^2	107 MW$^*{}_p$	Third
Waste-to-energy	2500 MW	25 MW$_e$	
Solar water heating	140 million m^2 collector area	0.68 million m^2 collector area	

*of this 46 MW$_p$ SPV products have been exported.

the potential from this source. Similarly, the respective installed biomass power and small hydropower capacities are about 2.4 and 9.8% of their potential.

4.5. Solar PV progress in India

India lies in the sunny belt of the world. The scope for generating power and thermal applications using solar energy is huge. Most parts of India get 300 days of sunshine a year, which makes the country a very promising place for solar energy utilization [34]. The daily average solar energy incident over India varies from 4 to 7 kW h/m^2 with the sunshine hours ranging between 2300 and 3200 per year, depending upon location [18]. The technical potential of solar energy in India is huge. The country receives enough solar energy to generate more than 500,000 TW h per year of electricity, assuming 10% conversion efficiency for PV modules. It is three orders of magnitude greater than the likely electricity demand for India by the year 2015.

The largest market for PV in India has been for applications such as telecom power, railway network, oil and gas sector, defense services and exports, with a currently installed aggregate capacity of 107 MW as shown in Fig. 7. The Indian PV industry today consists of nine companies that manufacture solar cells, 23 manufacture modules and about 60 companies that are in the business of systems integration. There is also a manufacturing capacity of about 2 million silicon wafers annually. The industry produced 11 MW_p of modules in the year 1999, having a turnover of about US$ 100 million. The national program initiated in the year 1975, is believed to be one of the largest demonstration PV program in the world today [34]. In 2001, the annual production of solar modules accounted for 11 MW capacity in India as shown in Fig. 4.

Electrification is one of the main infrastructure requirements for the overall rural development. There are about 80,000 unelectrified villages in the country. Of these villages, 18,000 cannot be electrified through extension of the conventional grid. A target for electrifying 5000 such villages has been fixed for the Tenth National Plan. So far, more than 2700 villages and hamlets have been electrified mainly using SPV systems [35].

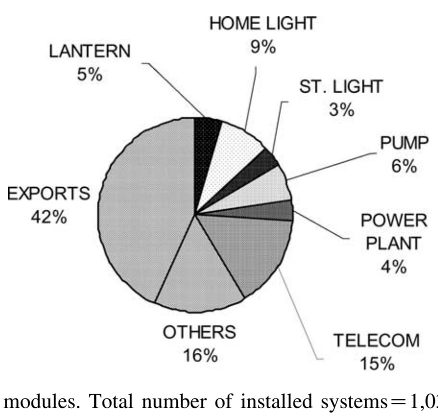


Fig. 7. Sectorwise use of PV modules. Total number of installed systems = 1,030,000. Aggregate capacity = 107 MW.

4.6. Proof of concept and economics of solar hydrogen

There are a number of solar hydrogen demonstration programs around the world—both for transport and building sector. The progress in the use of hydrogen as a fuel for transports has been presented in Section 3.4.2.

With respect to the building sector, once again, several such international demonstration programmes may be cited. One such reference [36] reports a 10-year operational experience. In the latter project, the technical feasibility of a self-sufficient energy supply system based on photovoltaic, battery and hydrogen storage was demonstrated for a public building: the Central Library in Forschungszentrum Jülich, Germany, for a period of 10 years. The overall efficiency based on the annual energy balance excluding the photovoltaic efficiency varied from 51 to 64%. The battery bank was able to supply energy to the load for three days in the absence of solar radiation. The battery delivered around 50–52% of the demand. In addition, another 20–25% of the demand was supplied by the fuel cell, which indicates that the energy should be stored in long-term storage system. A high level of energetic reliability with a relatively low battery capacity and hydrogen storage was thus demonstrated.

The economics of solar hydrogen in the proposed energy network can be categorised under three main areas: i.e. PV electricity generation, hydrogen production through electrolysis and storage of hydrogen. Producing energy through PV is presently more expensive than conventional energy systems primarily due to high cost of PV technology. PV, however, has significant long-term potential because it has very desirable attributes and a great potential for radical reduction in cost. The cost of PV module has been decreasing steadily over the years. The cost of PV has dropped dramatically, from US$ 7.4/W in 1987 to US$ 2.5/W in 2002 as shown in Fig. 8. Future forecasts indicate that cost of PV is likely to drop further over the coming years, approximately up to US$ 0.8/W by the year 2020 [37].

As stated above, hydrogen can be produced through a number of different technologies. All other technologies but electrolysis have associated carbon emission to various degrees that disqualify them as clean and environment friendly energy system. Electrolysis offers the main option for a zero carbon hydrogen economy that does not require sequestration.

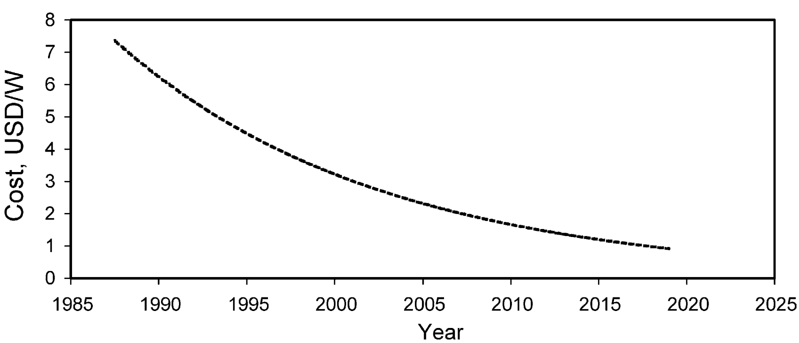


Fig. 8. Historical and projected PV cost.

PV-based electrolysis is although slightly more expensive than wind-based electrolysis, it, however, has been preferred due to its consistency and higher reliability as compared to the latter. Industry based estimates indicate that the cost of PV-based electrolysis in 2000 was US$ 41.8/GJ that is expected to drop down to US$ 24.8/GJ by year 2010 [38].

There are a number of technologies available for short-term and long-term storage. The three main options for hydrogen storage are compressed: hydrogen, liquid hydrogen and metal hydrides. Long-term storage of hydrogen in any of the three forms is much more expensive than for short-term storage. Liquid hydrogen is the cheapest storage option that costs around US$ 4.21/GJ for short-term (1–3 days) storage. The cost for long-term storage (30 days) of liquid hydrogen is around US$ 36.93/GJ [38].

4.7. Proposed energy network for key urban centres—a modular approach

4.7.1. Data processing

To develop a proposal for sustained solar energy development in the six major cities of India, the very first task was to explore the radiation data sets that were available for those sites. The pattern of the availability of solar resource, in time, is important, as this dictates the design of energy production, transmission and storage systems.

Chennai, Delhi, Jodhpur, Kolkata, Mumbai and Trivandrum were chosen in this study, because these are the chief metropolis of the Indian sub-continent. Furthermore, these sites are geographically and topographically different from each other as indicated in Table 8. The irradiance data of the former three sites were purchased by the authors from the India Meteorological Department expressly for the project under discussion. The radiation data sets of the latter three were extracted from the *Handbook of Solar Radiation* [39]. The present work employs detailed data sets of hourly global and diffuse values, day-by-day, for 12 months of each year over the period of 1990–1994 for the former three locations. The radiation sets from the above-mentioned handbook, on the other hand provide mean hourly values of the two irradiance components for the 12 months of the year based on observations made during the 10-year period 1958–1967.

It was noted that the data provided by the meteorological stations (Chennai, Delhi and Mumbai) were not diffuse corrected. To correct diffuse irradiance for the shadow band obstruction, Muneer and Zhang model was used [40]. As an example, the uncorrected data sets for Almeria (Spain) are shown, where the Drummond's model, usually adopted by the meteorological stations for diffuse correction, is shown to under-estimate

Table 8
Geography of the six cities chosen for the present study

Location	Latitude, N	Longitude, E	Height, MASL
New Delhi	28.60	77.20	236
Jodhpur	26.30	73.02	224
Calcutta	22.65	88.45	6
Mumbai	19.12	72.85	14
Chennai	13.00	80.18	16
Trivandrum	8.48	76.95	64

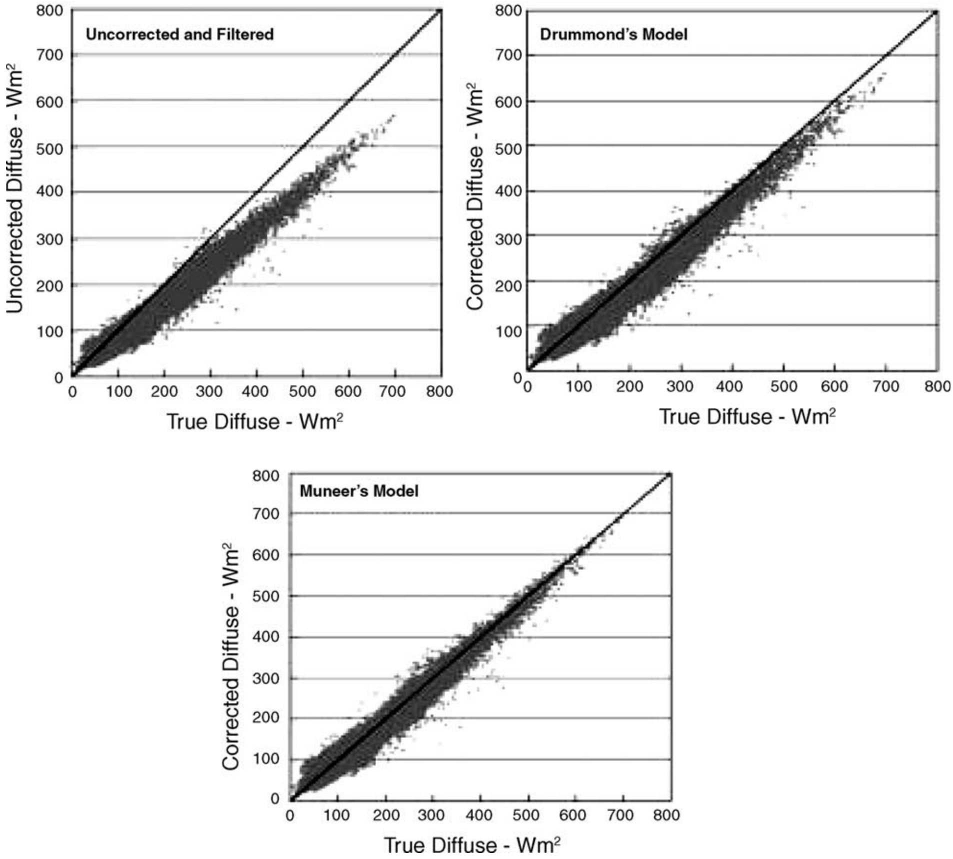


Fig. 9. A comparison of the two diffuse correction models for Almeria, Spain.

the correction. On the other hand, Muneer and Zhang model gives better estimates as shown in Fig. 9.

Close examination of the data reveals problems with the data quality, often for extended periods of time. Erroneous measurements can be due to a combination of factors like equipment error and uncertainty and operation related problems and errors. To correct those, a semi-automated procedure based on the creation of an envelope in the clearness index/diffuse to global irradiance ratio domain was developed. Details of that method that was used to produce a complete time-series of quality-controlled data are provided by Muneer and Fairooz [41]. The latter method was presently used to obtain quality-controlled data sets for Delhi, Mumbai and Chennai.

4.7.2. PV yield calculation

Hourly slope radiation values were calculated using a software tool from Muneer's monograph [42]. The computations were performed for five orientations using a PV area of 1 m^2 for each aspect, namely, east, southeast, south, southwest and west. Different

Table 9
Azimuth-tilt combinatorial sets and their respective PV energy yield

	Orientation		PV output with 10% efficiency (KW h per m^2)		
	Azimuth	Tilt	Delhi	Mumbai	Chennai
Case 1	90	90			
	135	90			
	180	90			
	225	90			
	270	90	148	134	128
Case 2	90	90			
	135	45			
	180	45			
	225	45			
	270	90	180	188	192
Case 3	90	45			
	135	45			
	180	45			
	225	45			
	270	45	205.6	216	228

combinations of tilts and azimuths were employed for the PV modules. A total of three cases were investigated details of which are shown in Table 9. The best set of orientations was worked out for each site in order to maximize the yield for a cost-effective arrangement of the PV array. For all of the three sites, case number 3 was found to provide the maximum slope irradiation as shown in Fig. 10. The energy yields were then summed up over the 5 years and annual yield was calculated taking a conservative efficiency of 10% for the PV modules.

Using the case 3 orientation, hourly PV yield profile for an average day of every month was calculated. Similar calculations were carried out for the mean-valued data for other three sites of Jodhpur, Kolkata and Trivandrum, for which only monthly averaged data were available. This PV yield profile was then set against the load profiles for

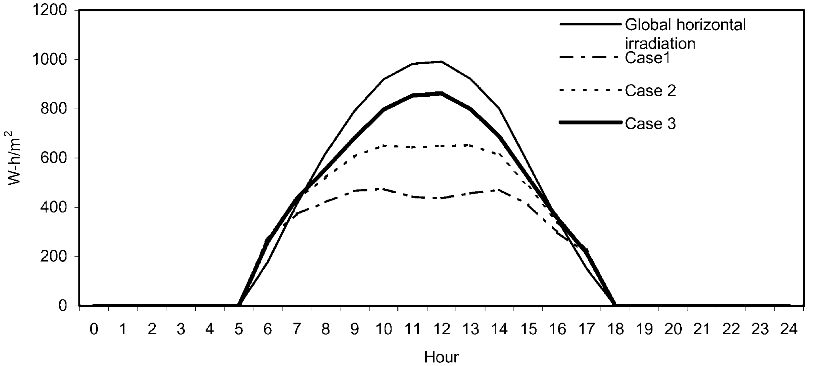


Fig. 10. Global horizontal and slope irradiation profiles for 14th April 1990 for Delhi (Table 9 refers).

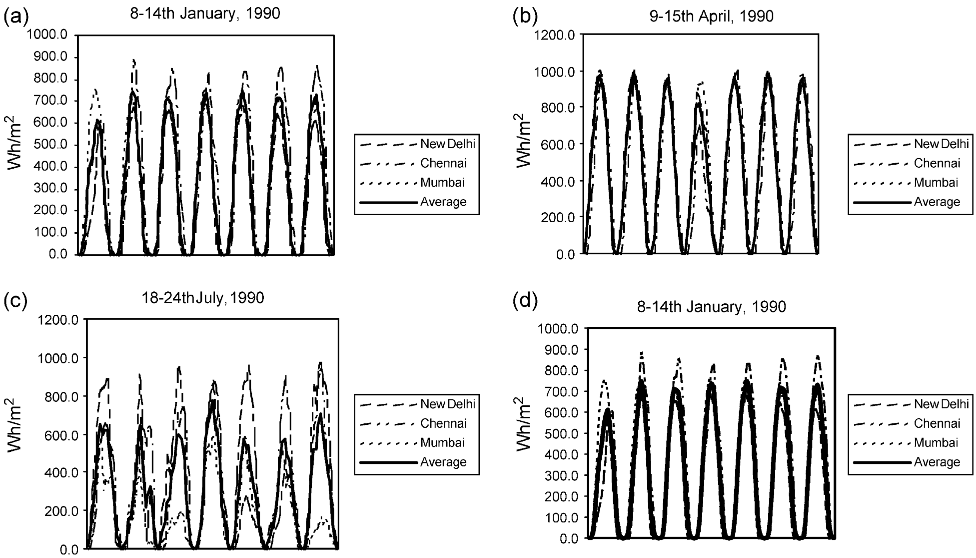


Fig. 11. Global radiation profiles and their overall averages for Chennai, Delhi and Mumbai for one week.

the six cities based on the predicted energy trends for 2025 to determine the required PV module area.

Presently, the main concern was proposing a solar electricity network for each of the individual cities under consideration. However, a grid-connected solar electricity scenario can be a viable option for the future. The main reason that it will smooth out the inherent fluctuations in solar radiation profile that are more site-specific and directly linked to the existing climatic conditions. Averaged global irradiance for the three locations of Chennai, Delhi and Mumbai were calculated. As expected, it was found that the site-integrated energy yield has a considerably more stable profile. In particular, for the month of July when most parts of India are affected by the seasonal monsoons and the irradiance trend vary widely the overall average of the three cities is fairly stable. Fig. 11 describes the global radiation profiles for Chennai, Delhi and Mumbai, with their overall average.

4.7.3. The modular energy network

The present work proposes solar hydrogen based energy network to meet the future energy demand for the major cities of India. This modular approach presents a sustainable energy solution to the ever growing energy needs in a way that is more secure, stable and environment friendly. In the proposed energy network very large-scale solar PV units are to be employed to generate electricity. Excessive solar electricity produced beyond the daytime needs is to be converted into hydrogen through electrolysis. The stored hydrogen is to meet energy requirements during nocturnal hours and also during heavily overcast conditions. Fuel cells are to be utilized to retrieve the energy stored in the form of hydrogen. The proposed energy setup also exploits a fossil fuel power system as a backup to provide electricity in case the demand exceeds available solar electricity and/or

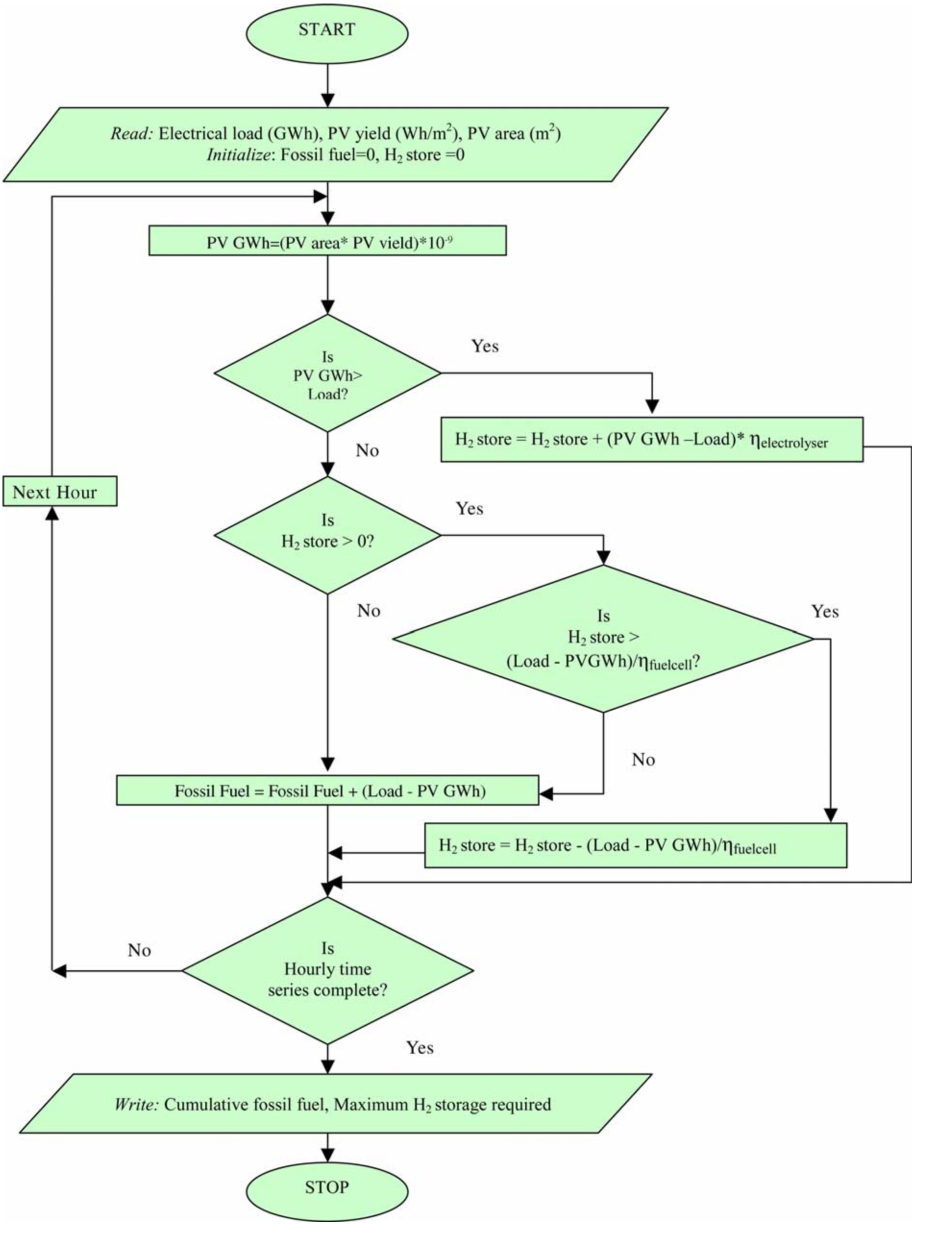


Fig. 12. Flow diagram for computation of solar electricity and hydrogen production and storage.

hydrogen. Fig. 12 provides functional details and flow chart for the energy supply and control mechanism for the proposed energy network. Present as well as projected cost scenarios for future have been provided for all the proposed technologies to evaluate the economical viability of the energy network.

Fossil fuel cost is expected to increase over the coming years as reported by numerous resources. Laherrère forecasts the crude oil price of US$ 22/barrel in 2003 to rise to US$ 27/barrel by 2025 that appears to be a rather conservative approach [43]. Exxon as indicated by Zittel, suggests a range of the crude oil cost for the year 2025 to lie between US$ 22 and 56 [44]. Relying on these predicted costs of crude oil, a range of the electricity cost in 2025 has been calculated. The electricity production cost (primarily fossil fuel based) in Delhi in the year 2003 was 7.6 US¢/kW h, while the projected cost of electricity in the year 2025 has been estimated to range from 9.3 to 19 US¢/kW h with a mean value of 14.2 US¢/kW h.

The cost analysis of the generation and transmission of solar PV electricity shows that the cost of PV cells is the most vital element. The worldwide market for PV has grown exponentially over last 20 years as PV cost has dropped dramatically, from US$ 7/W in 1988 to US$ 3/W in 2000 [37]. The PV cost in 2003, US$ 2.7/W, is projected to drop down to less than US$ 1/W by the year 2020. The trend described by Kurokawa leads to a PV cost of US$ 0.6/W by the year 2025 [37]. Based on 25-year service life for PV cells, the range of PV electricity production cost is calculated to be from 8.2 to 13.8 US¢/kW h with a mean value of 11 ¢/kW h. By 2025, the present day electrolysis cost of 15 US¢/kW h as reported by Padró, is expected to drop down to 4 US¢/kW h [45]. Hydrogen storage cost, for a facility size of 130 TJ, capable of supplying energy for 72 h in case of continuous spell of overcast conditions, is projected to be equivalent to 0.49 US¢/kW h [45]. By 2025, the present cost for proton exchange membrane fuel cells (PMEC), US$ 4.3/W, is projected to drop down to US$ 0.3/W [46]. Assuming a 10-year service life for fuel cells, the net energy cost is estimated to be 0.52 US¢/kW h by the year 2025.

A comparison of the present day costs of the technologies involved in proposed energy network with the projected costs for the year 2025 has been presented in Table 10. In the present study, Delhi's electricity demand in the year 2025 has been estimated based on its present load profile and India's total electricity demand in the year 2025 as reported by International Energy Outlook [47]. Delhi's electricity demand has been calculated on the basis of its population proportion in India. This 'business as usual' demand is estimated to be 28.8 TW h. According to world energy statistics, India at present is consuming 19% of world's average per capita energy [48]. Assuming that due to its rapid economic growth, by the year 2025, India will consume 35% of world's average per capita energy, Delhi's electricity demand is estimated to be equal to 38.8 TW h. The latter scenario will represent

Table 10
Cost analysis of proposed technologies

Technology/cost	2003 (US¢/kW h)	2025 (US¢/kW h)		
		Low	Medium	High
Fossil fuel	7.60	9.30	14.20	19.00
PV modules	3.70	8.20	11.00	13.80
Electrolysis	15.00	–	4.00	–
H_2 storage	1.90	–	0.49	–
Fuel cells	7.45	–	0.52	–

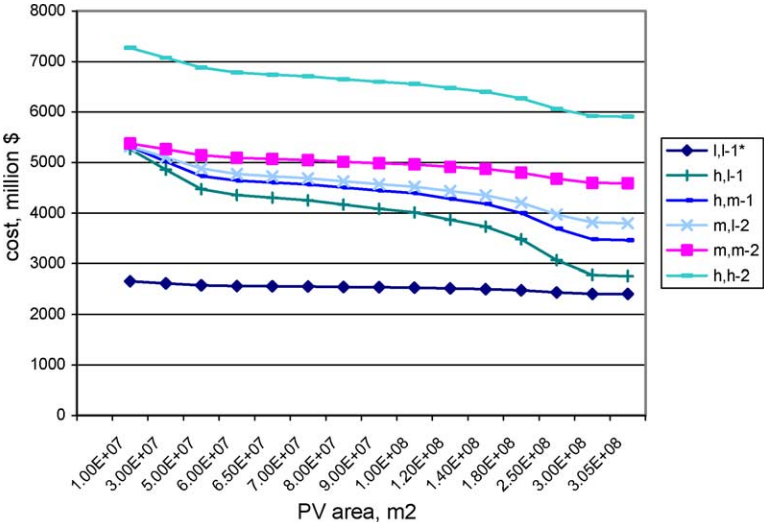


Fig. 13. Cost comparison for supply of fossil fuel and solar electricity for the year 2025: Delhi. l, low; m, medium; h, high; 1, business as usual scenario; 2, rapid economic growth (notations: first, fossil fuel cost; second, PV electricity cost; third, demand scenario).

a 'rapid economic growth' situation. The economics of the proposed energy network to meet Delhi's energy demand in the year 2025 with six different possible cost scenarios of involved technologies has been presented in Fig. 13. The cost scenarios describe the total cost of providing the electricity both for 'business as usual' and rapid economic growth energy demand of Delhi, utilizing different viable combinations of fossil fuel and solar

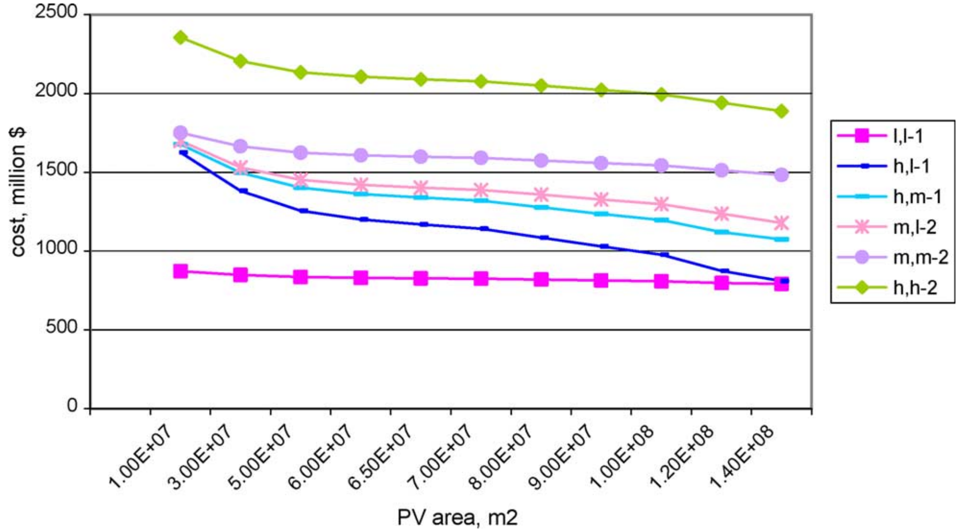


Fig. 14. Cost comparison for supply of fossil fuel and solar electricity for the year 2025: Chennai.

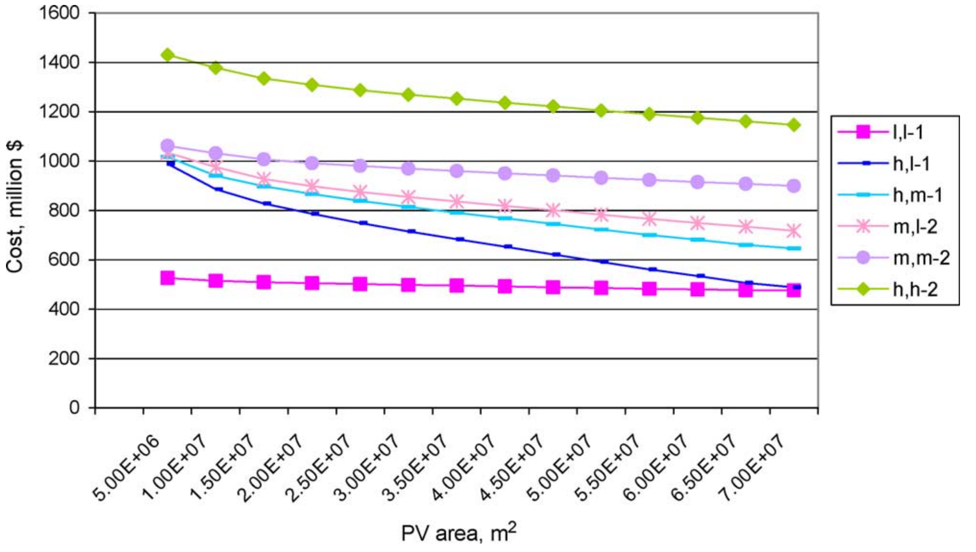


Fig. 15. Cost comparison for supply of fossil fuel and solar electricity for the year 2025: Jodhpur.

electricity at high, low and medium projected future costs. The electricity cost for the network has been plotted against increasing PV area. From the figure, it is noted that with a low projected fossil fuel cost and a low projected PV cost (l,l−1) the increase in PV area has only a slight bearing on the decrease in overall electricity generation cost. However, a significant decrease in overall cost can be observed even if the fossil fuel cost is medium like in the case m,l−2 with increase in PV area. The sharpest cost reduction is evident when PV cost tends to be low while fossil fuel cost is on the rise, i.e. h,l−1.

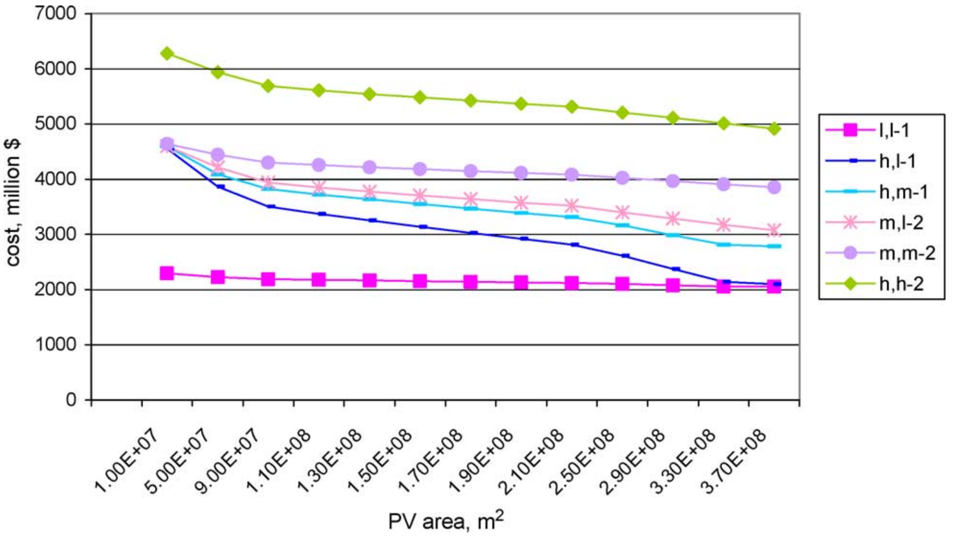


Fig. 16. Cost comparison for supply of fossil fuel and solar electricity for the year 2025: Kolkata.

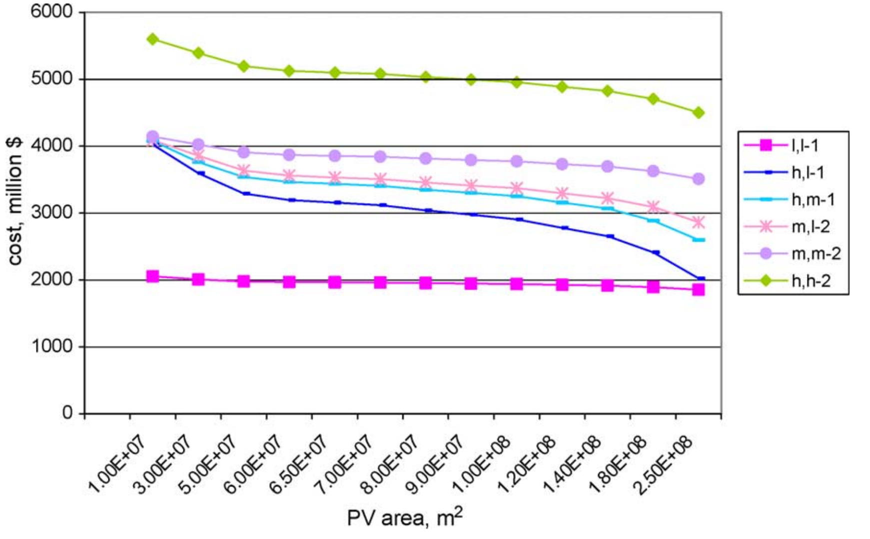


Fig. 17. Cost comparison for supply of fossil fuel and solar electricity for the year 2025: Mumbai.

With the continuing trends of consumption of fossil fuel and the environmental issues involved, it is highly likely that the fossil cost would witness a sharp rise in the future. By the year 2025, it is expected that with increasing global awareness and enhanced technologies, renewables will form a major portion of the energy matrix. Consequently, the PV technology if not cheaper would at least become competitive with the non-conventional energy resources in the market. Based on such foresight, we thus have five scenarios strongly supporting our case (Fig. 13), which is: the total electricity cost would

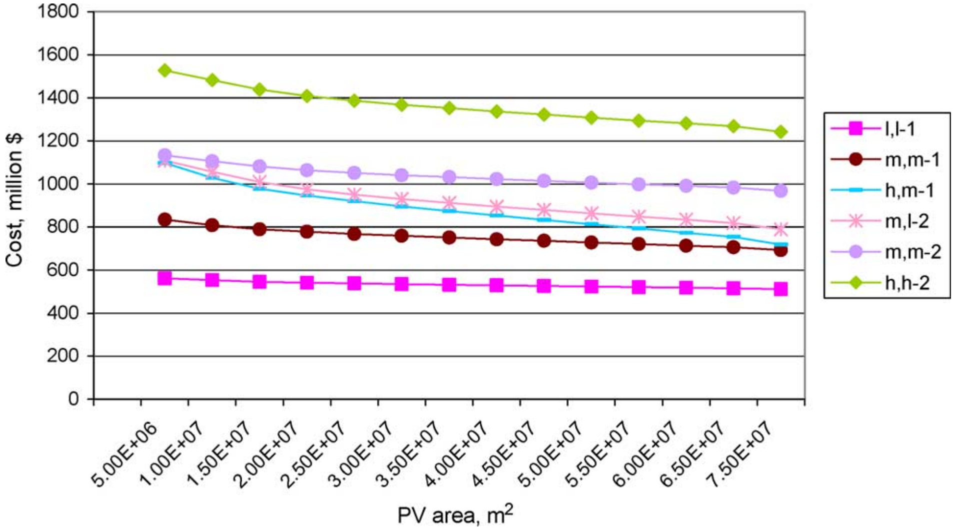


Fig. 18. Cost comparison for supply of fossil fuel and solar electricity for the year 2025: Trivandrum.

decrease considerably with a viable increase in the installed PV module area. Similar electricity network for the other major cities of India: Chennai, Jodhpur, Kolkata, Mumbai and Trivandrum and the related cost analysis were generated. They are provided in Figs. 14–18, respectively.

5. Conclusions

India, already being an energy deficient country inevitably requires to explore new avenues of generating electricity in a sustainable way to meet the future energy and its related environmental challenges. In present work, solar PV electricity has been described as the solution of future energy challenges. The modular approach adopted to meet the year 2025 energy demand of six major cities in India: Chennai, Delhi, Jodhpur, Kolkata, Mumbai and Trivandrum indicates that the suggested solar hydrogen based energy network has the capability of providing the energy requirements.

A cost analysis of solar and fossil fuel electricity suggests that at present fossil fuel electricity is more economical than the former. However, the projected future scenario indicates that the cost of fossil fuel electricity is to rise due to depletion of its resources. Solar electricity will see a substantial drop in its cost due to a gradual evolution of involved technologies, i.e. PV modules, electrolysis, hydrogen storage and fuel cells. The price trend indicates that by the year 2025 solar PV electricity will be more economical than fossil fuel electricity.

Acknowledgements

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